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CPT - Contraption for Probing in Tills?

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SYNOPSIS: The very complex till deposits encountered in connection with the establishment of the Storebælt Link have triggered an extensive application of CPT testing. The clay tills are inherently heterogeneous with a high content of very coarse particles up to boulder size. Due to varying degrees of overconsolidation they, furthermore, exhibit highly varying undrained strength in the range from 50 kPa to well over 1000 kPa. Despite these seemingly insurmountable difficulties CPT testing proved feasible. It allowed a much more detailed and varied picture of the stratigraphy and the geotechnical parameters compared with traditional field vane testing.

The vast number of CPT tests and adjacent borings with field vane tests allowed a comprehensive calibration of the cone factor, N_k, and evaluation of the influences of overburden, pore pressure and carbonate content.

In the paper the advantages and shortcomings of using offshore CPT testing to provide the geotechnical design basis for the foundation of the structural elements of the Storebælt Link bridges are described.

1. INTRODUCTION

The Storebælt Link project in Denmark has paved the road for several innovations and introduction of practices hitherto neglected or kept out by the force of tradition. As an example the acceptance of CPT testing in Denmark is closely linked to the project.

Due to the geological setting of Denmark, there is an abundance of stiff and hard soil types in marked contrast to the peats and soft clays of the Netherlands and other countries associated with extensive CPT testing. This certainly applies to the Storebælt area, where glacial tills, Selandian marl and Danian limestone (from the top down) are the main soil types in question. In a way both the owner (A/S Storebæltsforbindelsen) and the contractors were brave to instigate the more than 4000 m of CPT testing in soils with undrained shear strength typically from 250 kPa to well over 1000 kPa. In the early days a number of cones were lost due to teething problems but the overall experience and results have been very promising.

The paper will focus on the lessons learned from CPT testing particularly in clay tills for the Storebælt Link illustrated by some case histories.

A thorough discussion of the geology and the components of the Storebælt Link may be found in the Proceedings of the Eleventh European Conference on Soil Mechanics and Foundation Engineering, XI ECSMFE, volumes 5 and 11 (f. inst.. Foged et al; 1995).

2. STOREBÆLT TILLS IN SHORT

In the Storebælt region the basement strata consist of Maastrichtian chalk (Cretaceous deposits at depths exceeding some 85-100 m below the sea bed) and a Palaeocene sequence consisting of Danian limestone and Selandian marl. These layers are covered by Quaternary deposits comprising glacial, late glacial and Holocene deposits.

The predominant part of the Quaternary is the glacial sequence which lithologically is subdivided into an upper and lower glacial unit of tills and melt water deposits.

The upper unit is dominated by a single clay till deposit, the Sprogø till, with a maximum thickness of 25 m. For geotechnical reasons it was subdivided in Clay Tills 0, 0/1 and 1 according to limits of undrained shear strength of 100, 200 and 400 kPa, respectively.

Three till types (Till 2, 3 and 4) with associated melt water deposits may be distinguished in the lower unit. The strength of the lower tills is high, typically $c_u > 400$ kPa measured by field vane or CPT.

Thus, the glacial sequence is dominated by clay tills of highly varying strength with significant seams, lenses and layers of sand and gravel or sand till.

From the envelope of grain size curves for the clay tills shown in Figure 1 it is apparent that these deposits are very heterogeneous with a high content of coarse particles. Boulders occur frequently, more than 1 in 100 m^3, but it was established that the frequency of boulders decreases with a factor ten for an increase in boulder diameter by 0.5 m (Ditlevsen, 1989). This is of course not reflected in Figure 1 which is based on borehole samples.

According to the Danish soil classification system (Larsen et al, 1995) clay tills have a clay content not less than 12% and a plasticity index, $I_P > 4\%$. For the Storebælt region average values of clay content ≈ 15-17% , $I_P \approx 6\text{-}7\%$ and natural water content $w \approx 10\text{-}12\%$ are found. In general the carbonate content ($CaCO_3$) is 17-22% but in the lower till unit deposits characterised as Till, very calcareous ($CaCO_3$ content in the range 35-70%) were identified. By triaxial testing it was established, however, that the undrained behaviour is similar to that of clay tills.

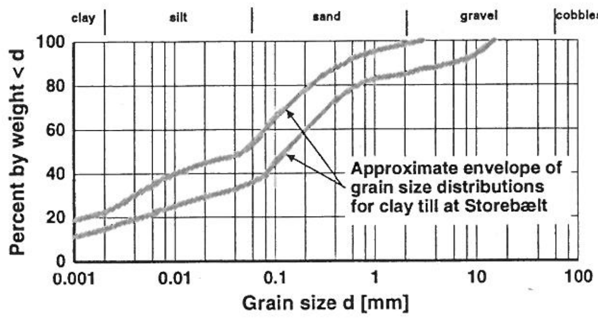

Fig.1 Grain size of clay tills at Storebælt

3. STRENGTH TESTING OF THE TILLS

Soil investigation campaigns of 1962-63, 1977-78 and 1983 - preceding the final campaign for the Storebælt Link presently being finalised, starting in 1986 - were based on geotechnical borings, laboratory testing and seismic profiling.

The strength of the clay tills was inferred from field vane tests (FVT) - based on "well-winnowed experience" of several decades in Denmark using the Danish deep vane system and it was tacitly assumed that the standard interpretation was valid for the tills of Storebælt:

$$c_u \approx c_{u,vane} \tag{1}$$

However, due to the high cost of drilling offshore geotechnical boreholes the client decided to add CPT testing when the detailed investigations for the West bridge were initiated at an average ratio of 8 CPTs to 2 boreholes for each of the 62 offshore piers.

The CPT tests were performed by Fugro-McClelland with additional tests carried out by the Danish Geotechnical Institute. At an early stage (DGI POS 68 , 1989) a rough calibration of CPT and VST, based on 170 m of penetrated Clay Till 1, indicated a cone factor of 10. Taking more than 500 data points of neighbouring CPT and FVT (mathematically smoothed CPT profiles with a 0.21 m bandwidth average value at the level of VST value without refusal or stones) cone factors without and with correction for overburden stress σ_v

$$N_k = \frac{q_c}{c_{u,vane}} = 10 \tag{2}$$

$$N_{kt} = \frac{q_c - \sigma_v}{c_{u,vane}} = 10 \qquad (3)$$

were confirmed to represent equally best fits for the West Bridge data (Mortensen et al, 1991).

Both the $c_{u,vane}$ and q_c values were log normally distributed, but with the coefficient of variations of 0.36 and 0.20, respectively, the CPT test is the better predictor.

Subsequent, extensive CPT testing (some 400 CPTs to app. 20 m depth) by the Danish Geotechnical Institute for the East Bridge, including CPT tests close to some of the borings from the 1962-1963 campaign confirmed the general validity of (2) as a very robust cone factor. However for Clay Till 0 ($c_{u,vane} < 100$ kPa) Eq (3) with q_c substituted by q_T, i.e. with correction for pore pressure, should be applied to obtain relevant strength values.

4. CPT versus VST

The field vane profiles very clearly indicate the problems associated with in situ strength testing of the tills. On numerous occasions refusal or influence from "stones" are reported in the field journals. This results in jagged undrained strength profiles where any naturally occurring trending with depth may vanish.

It is therefore little wonder that the "foreigners" on the Storebælt project were dubious about the ability by the Danes to assess the undrained strength. This is moreover amplified by a general feeling of inadequacy of VST data for overconsolidated clays as reported by Young et al (1988).

In response to a questionnaire concerning VST testing for design purposes only 6% of the respondents indicated that VST would be useful if OCR>4. Indeed only a minority felt that VST could be performed in soils stronger than 225 kPa and 60% believed the practical limit of the test to be 150 to 200 kPa!

Thus considering the typical strength distribution found for the "weaker" Upper Till in the Storebælt region (Figure 2) conditions would indeed appear dire. Note, that the relatively high number of values 325 kPa < $c_{u,vane}$ < 350 kPa and 700 kPa < $c_{u,vane}$ < 725 kPa corresponds to refusal for the two types of vanes applied (at 365 and 714 kPa, respectively).

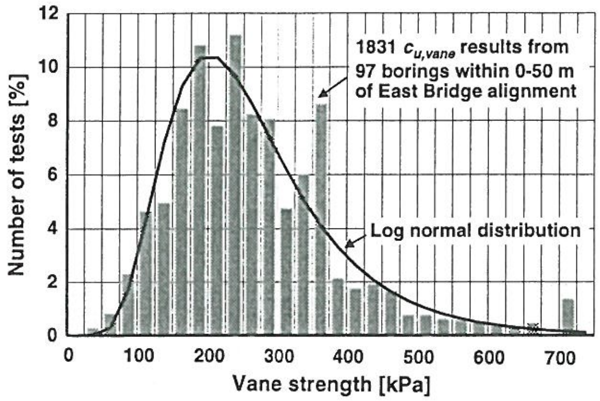

Fig. 2 Strength distribution in Upper Till

The results in Figure 2 are drawn directly from the Storebælt GEOMODEL data base (for a description see Porsvig and Christensen, 1994).

The occurrence of the stones/boulders and the highly varying strength naturally affects the CPT profile as well. However, due to the continuous registration it is possible to reduce the spiky appearance of the profiles by mathematical smoothing. Thus, if the coarse particles due not break the cone it is still possible to provide meaningful data. The stones in the clay till has by far the biggest impact on the sleeve friction and the pore pressure measurements. Omission (by mistake) of a stop criterion for the sleeve friction in the Project Quality Plan led to a relatively high loss of cones until proper stop criteria were established.

As a consequence and drawing on the experience gained at Storebælt in general the Danish Geotechnical Institute has introduced the following stop criteria for its offshore dedicated CPT rig SCOPE (used for more than 2000 m of CPT testing on Storebælt) in order to accept the risk of loosing cones due to soil conditions:

- maximum thrust: 200 kN
- maximum tip resistance: 80 MPa
- maximum sleeve friction: 0.53 MPa
- maximum sudden increase in inclination with high tip resistance: 3°
- maximum inclination with vertical: 20°

These stop criteria have very significantly reduced the loss of cones, and importantly have ensured that data are not invalidated due to damaged but not malfunctioning probes. This is particularly important for offshore applications where cost-benefit considerations require that the rig stays submerged during location changes, f. inst. within a pier position.

During penetration in the tills the high content of coarse materials has the consequence that pore pressure measurements are dubious. Upon contact with a stone the pore pressure drops almost instantaneously to zero or even negative values. Only in the softest tills c_u < 100 kPa or notably at the transition between Upper and Lower till formations were high pore pressures recorded.

The latter highlights one of the shortcoming of alone-standing CPTs. The geologically interpreted boundary between Upper and Lower Till Units is almost unequivocally identified by the CPT tests as a sudden significant increase in tip resistance, q_c, and sleeve friction, f_s. However, for a considerable number of CPTs a decrease in q_c accompanied by significant pore pressure increases were seen at the approach to the Lower Till Unit. An interpretation in terms of undrained shear strength may therefore be misleading and the lower tip resistance may be a bogus measurement. The reduction in resistance may instead be a tell tale of presence of silt, lime or sand and the "dynamic" effect of the testing method in these materials better represented by drained strength parameters.

5. CASE HISTORIES

5.1 Strength model, East Bridge

Being the last of the three main components to be constructed, the East Bridge designers could draw upon the experience and data gained from the West Bridge and the East Tunnel.

Hence the dedicated CPT test, vane tests and laboratory tests, notably triaxial compression tests, were cross calibrated very carefully to furnish a strength model for the intact clay till (Upper Till) to be used in the design basis.

To limit the number of independent variables it was decided to accept a cone factor of N_{kt} = 10. The calibration resulted in (Sørensen et al, 1995)

$$\begin{aligned} c_{u,c} &= 0.42\sigma_v'\left(\sigma_{pc}'/\sigma_v'\right)^{0.85} \\ s_{u,vane} &= 0.88c_{u,c} \\ s_{u,vane} &= q_c/10 \end{aligned} \tag{4}$$

In (4a) the overall factor 0.4 has been replaced by the specific value of 0.42.

It is apparent that (4b) differs from (1). This is a result of the choice of cone factor N_{kt} = 10 in (4c). However, if the proposal by Luke (1994),

$$\left.\begin{aligned} c_{u,c} &= \left(q_T-\sigma_v\right)/10 \\ c_{u,vane} &= \left(q_T-\sigma_v\right)/\left[15\left(f_R\%\right)^{-0.4}\right] \end{aligned}\right\} \Rightarrow \qquad \frac{c_{u,vane}}{c_{u,c}} = 0.67\left(f_R\%\right)^{0.4} \tag{5}$$

where f_R is the friction ratio, is adopted this may explain the deviation. Inserting the typical value of f_R = 2% (5c) gives a ratio of 0.88, i.e. as in (4b), whereas f_R = 3% gives a ratio of 1.03 corresponding to (1). Hence a cone factor of N_{kt} = 11.4 (f_R = 2%) in (4c) would change (4b) into (1).

This clearly demonstrates that correlations are no better than the data base and that they should be used with very open eyes particularly as most correlation systems work as a Pandora's box.

During the calibration, attempts were made to correlate the cone factor with the activity A (ratio of % clay content and I_P). However, since the activity is mainly an indicator of clay mineralogy, with no apparent physical link to the cone factor, and values of A = 0.2 - 0.6 are found rather irregularly for the clay till samples, this should be done with caution.

5.2 Strength anomaly - lime content

During foundation inspection for the West Bridge piers supplementary soil investigations revealed areas with low values of CPT and vane resistances in a layer of the Lower Till Unit. Borings revealed low activity ($A \approx 0.2$ compared with average of ≈ 0.4) due to high $CaCO_3$ content. The soil was therefore termed Till, very calcareous but the grain size curve corresponds to clay till.

The same type of soil, albeit with lower $CaCO_3$ content and higher activity, had been found about 25 years before at an onshore site some 50 km from Storebælt. CPT testing close to the original borings were carried out to provide a comparison and update of the cone factor N_k for this soil type (DGI POS 162, 1992). The trends of CPT and vane strength values from the offshore piers and the onshore site were similar and unequivocally indicated the use of a cone factor $N_k \approx 8$ instead of the "universal" value of 10, Eq (1).

The vane tests at the onshore site were strongly affected by stones, whereas the CPT profiles, when aggregated, showed a wery clear trend with spikes (stones?) at exactly the same depths. Note, that the friction ratios f_R were 2-5% as opposed to the values of 1.5-2% typical of the "normal" Storebælt clay till . According to (5) this might indicate a reduction in cone factor.

The effect of the high $CaCO_3$ content seems to be added structure - and accompanying strength - of the till with a ratio of $c_u/\sigma'_v \approx$ 0.48-0.60 instead of the value 0.40 generally accepted for the West Bridge tests.

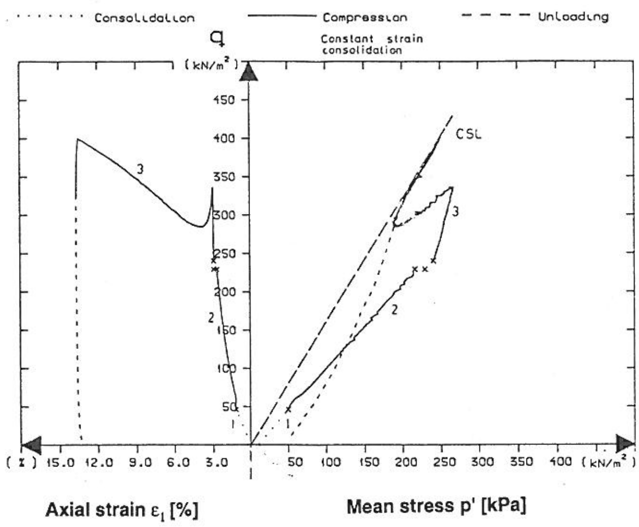

Fig. 3 $ACU_{u=0}$ triaxial test on Till, very calcareous (deviator stress q versus mean stress p' and axial strain ε_1)

The anisotropically consolidated, undrained triaxial test of Figure 3 shows a pronounced peak strength followed by strain softening and subsequent dilational behaviour at increasing strain level.

5.3 Strength anomaly - soft clay till

In general the designers gained high confidence in the use of undrained shear strength inferred from the CPT tests in the Upper Clay Till.

However, for some of the East Bridge piers, notably Pier EB04, low strength areas were studied by laboratory testing too as values of vane strength down to 30 kPa (single value) were recorded. The lowest strengths were found to correspond to water contents higher than average and using full correction for pore pressure the CPT induced strengths were only slightly higher than the vane strengths.

Using (4a), OCR values close to unity could not be ruled out for some of the specimens. This was in contrast to previous findings for Clay Till 0/1-1, where all specimens were found to be strongly overconsolidated (OCR from 5 to 20).

The conclusions from the results of four triaxial tests of low-strength clay till were

- presence of strong stress path dependant strength anisotropy
- transition to behaviour as remoulded clay till when the pre-consolidation pressure was exceeded
- a reduced strength ratio $c_u/\sigma'_v \approx$ 0.32 (compared with the 0.42 of (4a)) was recommended for design purposes.

The CPT testing was not invalidated, but again caution is recommended in application of the promising "ubiquitous" extrapolation tools.

6. LESSONS LEARNED

The extensive CPT-testing (more than 4000 m penetration) applied for the Storebælt Link Project has facilitated a very thorough calibration with the Danish "well-winnowed experience" of vane shear strength measurements in clay tills. An overall robust cone factor of $N_k \approx$ 10 proved applicable, but adjustments were called for in low strength areas (where use of

N_{kt}, i.e. with correction for both overburden and pore pressure, is essential) or in areas with lithology differing from the average (f. inst. high $CaCO_3$ content).

Despite the very heterogeneous nature of the tills with a high content of coarse particles and highly varying undrained shear strength (from below 50 to well over 1000 kPa) penetration with standard cones (1000 mm^2) proved very feasible. In general they were found to be better than enlarged cones.

Due to the reduced cost of CPT, compared with offshore borings, CPT testing was found to be a valuable tool in verification of seismically determined soil boundaries and delineation of areas with anomalous soil properties.

To gain full use of the CPT results it is essential that the CPT-profiles are mathematically smoothed to reduce the inherent spiky appearance dictated by the coarse particles. Moreover aggregated profiles of neighbouring CPTs, f.inst. within a pier, was a valuable tool in assessing anomalous strength behaviour and delineation of boundaries horizontally.

However, the overriding message from the CPT experience from Storebælt is the need for integration of testing tools (seismic profiling, borings, in situ tests and laboratory tests). Application of one tool alone may seriously limit the possibility of rendering "a complete picture" for the purpose of facilitating a safe and economical design.

7. ACKNOWLEDGEMENTS

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